Indian J. Phys. 78B(1), 47–53 (2004)

Latitudinal variations of strength of ionospheric response and its correlation with intensity of magnetic storms

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Receivied 2 April 2003, accepted 19 November 2003

Abstract : A study has been made to investigate the latitudinal variations of the 'strength of the ionospheric response' to positive and negative weak as well as major magnetic storms by considering low (Ramey), mid (Sagamore Hill) and high (Goose Bay) latitude stations during the years 1980-81. The nature of the correlation that exists between the strength of the response and intensity of positive and negative magnetic storms at various latitudes has also been checked. In the case of weak and major positive storms, the lowest strengths of response are shown respectively by the mid and high latitude stations, while the highest strength of response, for both categories of storms, is shown by the low latitude station. For weak and major negative storms, the lowest strengths of response are again shown respectively by the mid and high latitude stations; in contrast, the highest strengths are exhibited respectively by the high and mid latitude stations. The strength of the response during major positive storms, in general increases with decreasing latitude. A positive correlation was found to exist between the strength of the response and the intensity of storms during weak and major positive storms for the low latitude station, Ramey. A similar trend was also seen for low and mid latitude stations during major negative storms. However, in the case of weak negative storms, a negative correlation was found to exist between the strength of the response and the intensity of storms for all the three latitudes, contrary to the previous studies for low latitudes during negative storms. Also, a negative correlation is observed between the intensity and time delay for maximum ionospheric response, in the case of positive weak storms for low latitude and negative weak storms for high latitude.

Keywords : Magnetic storms, ionospheric response, latitudinal variations.

PACS Nos. : 94.30.Lr, 94.20.–y

1. Introduction

A magnetic storm is a period of intense energy input from the magnetosphere, leading to profound changes in the global morphology of the upper atmosphere. Such perturbations form an important link in the complex chain of solar-terrestrial relations since their ultimate source of energy is the solar wind. They are of great practical interest since they shorten the life spans of satellites, degrade satellite predictions, and disturb trans-ionospheric radio communications [1].

When the Earth's magnetic field undergoes a change due to the impact of solar wind particles of increased speed, a geomagnetic storm occurs. Thus geomagnetic storm will produce energy inputs like enhanced electric fields, currents, and energetic particle precipitation. Infact, ionospheric storms are resulting from large engergy inputs to the upper atmosphere, associated with geomagnetic storms. During ionospheric storms, various ionospheric parameters will show considerable deviations from their average behaviour. Among various ionospheric parameters, total electron (TEC) of the ionosphere is selected for this study which is a measure of the total number of electrons in a vertical column of unit cross section extending from ground to the top to the ionosphere.

TEC observations have yielded valuable information on many ionospheric processes and have also helped to

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evaluate the gross ionospheric effects of trans-ionospheric statellite, radar and radio-astronomical measurements. Storm time features like, time of occurrence, time delay, time duration and strength of ionospheric response for a low latitude station Palehua were studied previously [2,3]. The very few previous studies conducted on this aspects were done on single station and with out classifying the storms as weak and major storms. However, the new features of the present study is the latitudinal aspects of the correlation between various storm time parameters by classifying the storms as weak and major storms.

If we consider all storms together, for a statistical study (weak storms as well as major storms together), some of the prominent storm time ionospheric responses contributed by major storms may be nullified (or unnoticed) due to the effect of certain weak storms. Hence, for conducting a statistical study of ionospheric responses dutring storms, it is highly essential to classify storms in accordance with their Dst index. In the present study, we have categorised storms during the period 1980-81, as weak storms with Dst > –100 nT and major storms with Dst < –100 nT, which included both moderate and strong storms [4,5].

A prediction of TEC is essential to apply ionospheric corrections to operational systems. Suitable mathematical models can describe diurnal and seasonal variations of TEC and help to predict the data in terms of harmonic coefficients of TEC variations [6]. First-principle theoretical models have now reproduced the global scale characteristics of ionospheric storms, but local features during specific storms are difficult accurately predict largely due to uncertains in the inputs required by the models [7].

The present study investigate the latitudinal variations of the strength of ionospheric response to positive and negative weak and strong storms by considering low (Ramey), mid (Sagamore Hill) and high (Goose Bay) latitude stations. It also checks for any correlation that could exist between the strength of these responses and the intensity of the storms at various latitudes.

2. Data and analysis

Hourly values of TEC obtained by the geo-stationary satellite ATS 5 during the years 1980-81 for low (Ramey : Geomagnetic latitude 28.7°N, Geographic latitude 17°N and Geographic longitude 289°E), mid (Sagamore Hill : 50°N, 42.6°N 298°E) and high (Goose Bay : 58.6°N, 47°N, 286°E) latitude stations were used for this study.

All the magnetic storms during the years 1980-81 were selected for the study and these were then classified as 'weak storms' (with Dst > –100 nT) and 'major storms' (with Dst < –100 nT). For each storm, five quiet days with Ap < 10 were selected prior to the storm day for finding the quiet time average. The weak and major storms were then classified as positive and negative storms depending on whether the dominant storm time deviation (ΔTEC) was positive or negative with respect to the quiet time average.

The maximum positive (for positve storms) and negative (for negative storms) deviations from the corresponding average values were found for each storm, which is termed as the 'strength of the ionospheric response' to the storm. The maximum Ap values during the storm periods were used to represent the intensity of the geomagnetic storms. It may be noted that the 'strength' always refers the strength of ionospheric response to geomagnetic storms while 'intensity' gives the measure of the intensity of geomagnetic storm.

3. Results

Figure 1 shows the latitudinal dependence of the strength of the response to (a) weak and major positive storms and (b) weak and major negative storms. In the case of weak

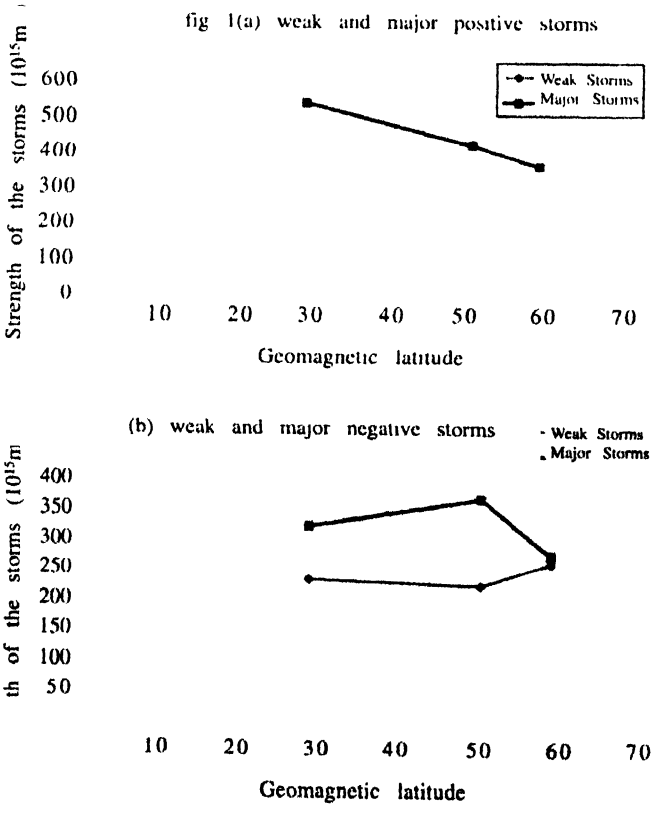

Figure 1. The latitudinal dependence of the strength of the response to (a) weak and major positive storms and (b) weak and major negative storms.

and major positive storms, the lowest strengths of responses are shown respectively by the mid and high latitude stations; while the highest strengths of response are exhibited by the low latitude station for both categories of storms. For weak and major negative storms, the lowest strengths are shown respectively by the mid and high latitude stations. In contrast, the highest strengths of response are exhibited respectively by the high and mid latitude stations. We also find that in the case of major storms, the strengths of the responses to positive storms are higher than those of the responses to negative storms for all the three latitudes where as both are almost same for weak storms. Also, for all the three latitudes, the strengths during major storms are higher than those during weak storms. Moreover, the strength of the response during positive major storms increases with decreasing latitude.

Figure 2 represents the dependence of the strength (ΔTEC) on intensity (Ap) of magnetic storms during positive

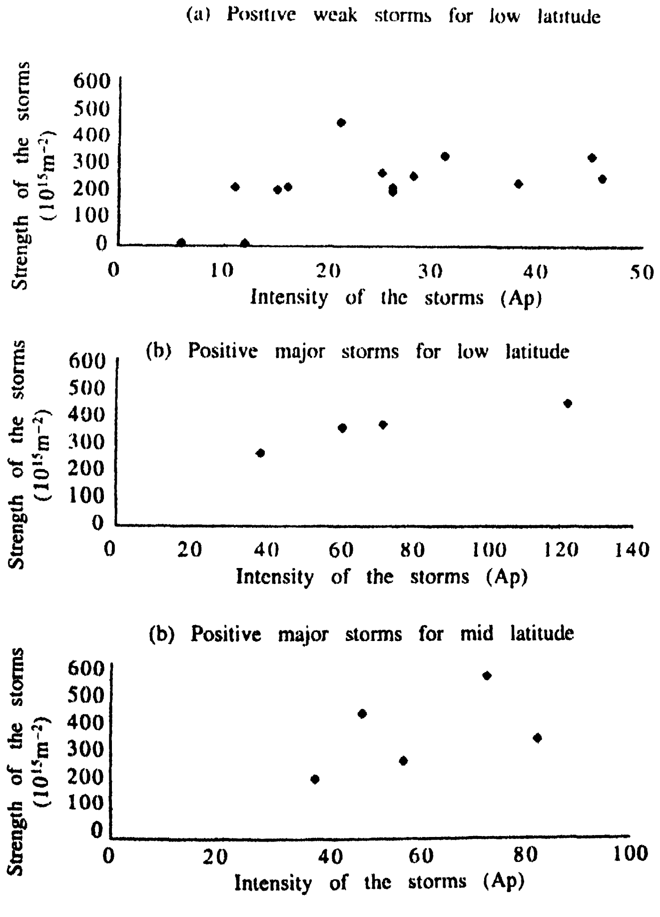

Figure 2. The dependence of the strength (ΔTEC) on intensity (Ap) of magnetic storms during positive (a) weak, (b) major storms for the low latitude station and (c) that during positive major storms for the mid latitude station.

(a) weak, (b) major storms for the low latitude station and (c) that during positive major storms for the mid latitude station. We find that a positive correlation exists between the strength of the response and the intensity of magnetic

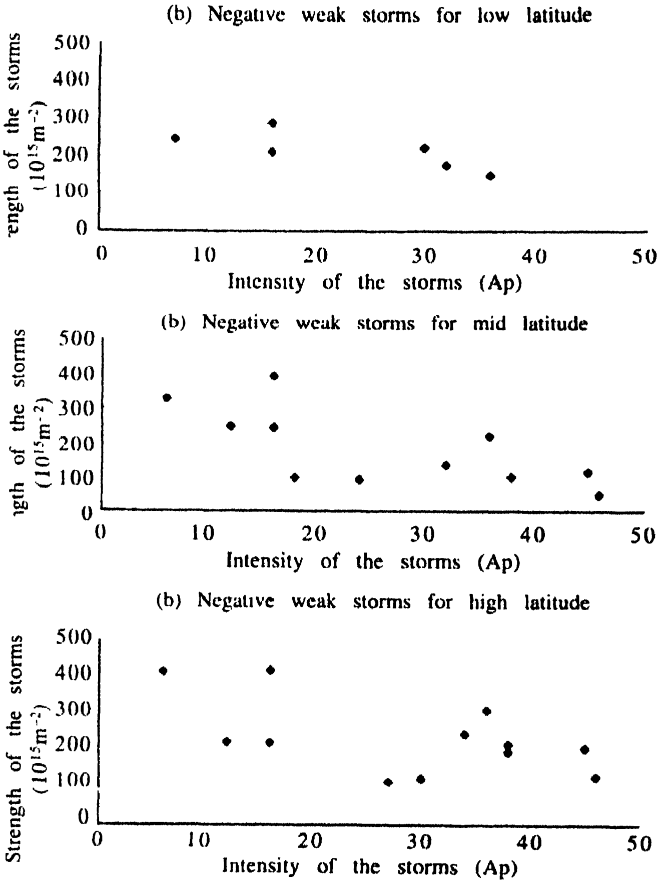

Figure 3. The dependence of the strength (ΔTEC) on intensity (Ap) of weak negative storms for (a) low, (b) mid and (c) high latitude station.

storms. The correlation coefficient observed between the strength and intensity during positive weak and major storms for the low latitude station are respectively 0.5365 and 0.9634. However, in the case of weak negative storms (Figure 3) a negative correlation exists between the strength of the response and the intensity of the storms for all the three latitudes contrary to the previous studies for low latitudes during negative storms. The correlation coefficient observed between the strength and intensity during weak negative storms for low, mid and high latitude stations are respectively –0.7421, –0.6902 and –0.55017.

In the case of major negative storms, we observe a positive correlation between the strength and the intensity of storms for (a) low and (b) mid latitude stations (Figure 4). The correlation coefficient observed between the

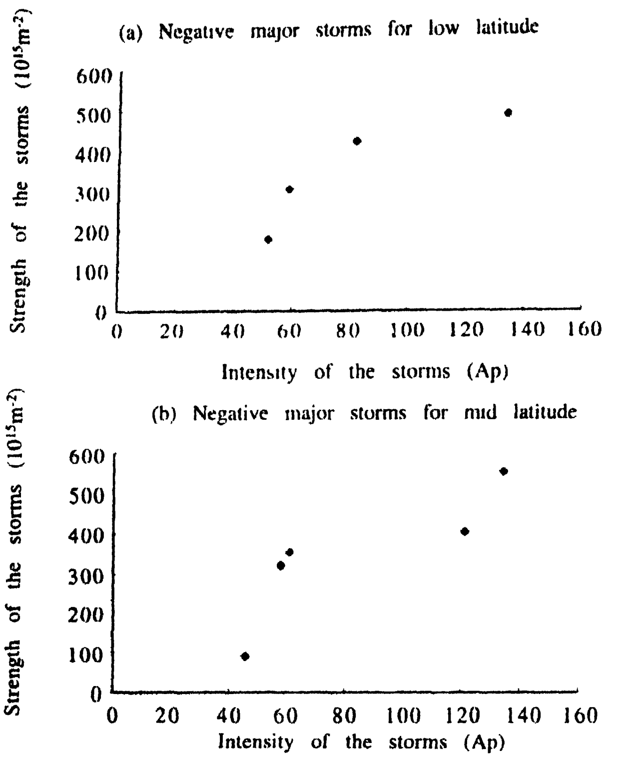

Figure 4. The dependence of the strength (ΔTEC) on intensity (Ap) of major negative storms for (a) low and (b) mid latitude stations

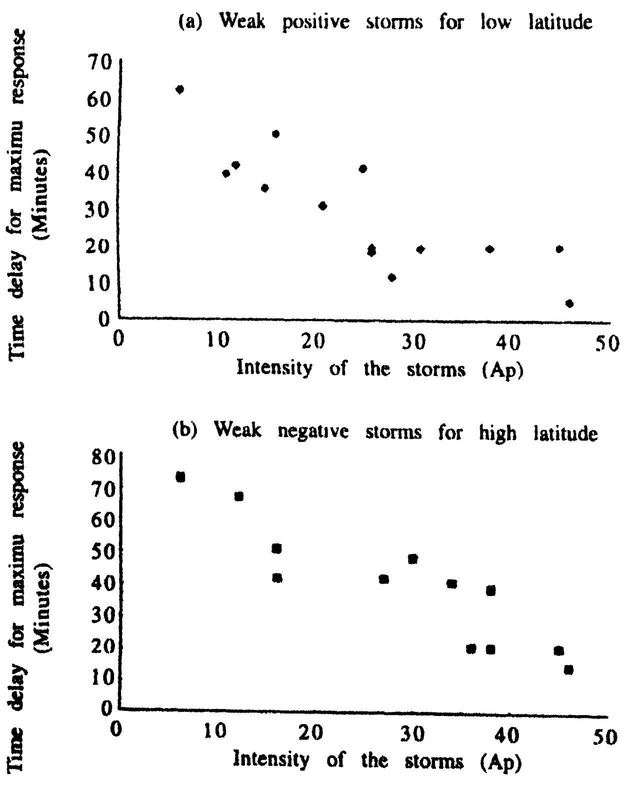

Figure 5. The dependence of the time delay for maximum response (τ) on intensity (Ap) of weak (a) positive storms for low and (b) negative storms for high latitude stations.

strength and intensity during major negative storms for low and mid latitude stations are respectively 0.8814 and 0.8401.

Also, a negative correlation is observed between the intensity and time delay for maximum ionospheric response, in the case of positive weak storms for low latitude and negative weak storms for high latitude stations (Figure 5). The correlation coefficient obseved between the intensity and the time delay for maximum ionospheric response, in the case of positive weak storms for low latitude and negative weak storms for high latitude are respectively –0.8642 and – 0.8994.

4. Discussion

Storm time studies have been conducted for low latitude stations like Hawaii and Palehua found that the time response of the ionosphere depended on the local time of sudden commencement rather than the main phase onset of the strom [8–10]. Also, the typical storm effects at the low latitude stations were an initial increase followed by a decrease.

In another study, more than 60 sudden commencement storms were anlaysed by considering the TEC of Hawai and Hamilton duing the period 1968-72. In a recent study, 68 storms were studied for a low latitude station Palehua and in both the studies positive correlations were observed between the strength of the responses and the intensities during positive and negative storms. However, in the present study, a negative correlation has been found to exist between the strength of the response and the intensity of weak negative storms for all the three latitudes.

The possible processes which might contribute to magnetic storm associated ionospheric varations are : (a) electromagnetic drifts associated with storm time electric fields, (b) enhanced thermospheric circulations (waves and winds) generated by auroral zone heating during magnetic storms and the consequent increased loss rates, (c) changes in atmospheric composition due to enriched thermospheric circulations and (d) compression of the plasmasphere by the enhanced solar wind.

The long duration positive storm effects are caused by changes in the large-scale wind circulations. At low latitudes the electrodynamic ExB drift is very effective in transporting ionisation in the ionosphere [11,12]. It is also known that, at low latitudes, atomic oxygen is enhanced by transport from higher latitudes and/or the upwelling in the auroral oval [13,14]. This, combined with the upward lifting of ionised medium caused by storm time eastward electric fields and equatorward neutral air winds would give prolonged enhancements in electron density values and TEC [15]. This could be the reason for higher strengths of response during weak and major positive storms observed by the low latitude station.

The positive ionospheric responses (positive storms) are caused by two different mechanisms : downwelling of neutral atomic oxygen and uplifting of the F layer due to winds. Both these relay of large scale changes in the thermospheric circulation caused by heating in the auroral zone. As the intensity of the geomagnetic storm increases, these two mechanisms will be more active and subsequently ionospheric responses will be more strong. This is the reason why the strength of ionospheric response increases with increase in intensity of geomagnetic storm, both in the case of weak and major positive storms.

In the case of weak negative storms, negative ionospheric response varies inversely with intensity of magnetic storms (Figure 3). This is because, as the intensity of magnetic storms increases, the causative mechanisms behind positive storm effects, like upwelling of ionospheric F2 layer and downwelling of O^+ ions would cause an increase in TEC and the negative ionospheric response ($-\Delta$TEC) will loose its dominance [16,17]. Therefore, in the case of weak negative storms, as the intensity of magentic storm increases, the negative ionospheric storm looses its dominance and its strength begins to vary inversely with the intensity of magnetic storm.

The prominent negative phase of the ionospheric response (negative storms) is generally caused by the neutral composition changes [18]. The composition disturbance zone is characterised by the decrease in O/N_2 neutral density ratio. The decrease in the composition ratio O^+/O or O^+/N will result in lower ionisation density. Also, in the case of negative major storms, the movement of composition disturbance zone is more effective. Hence, we can say that the neutral composition changes have a prominent role in producing negative ionospheric responses during both weak and major storms. In addition to this, the recent studies have revealed that the effect of vibrationally excited molecular nitrogen (N_2*) could increase the negative ionospheric responses, especially during negative major storms [19]. The recent work show better agreement between data and models if vibrationally excited molecular nitrogen (N_2*) is taken into account, especially during major storms [20]. Hence the influence of vibrationally excited molecular nitrogen (N_2*) must also be considered during the major negative phase. This is the reason why the strength of major negative storm increases with the intensity of magnetic storm.

During magnetic storms, a large amount of energy is dissipated in the polar regions. As a result of the upper atmospheric heating at high latitudes, atmospheric circulations are generated near the turbopause in both hemispheres [21,22]. Air thus moves up at high latitudes followed by an equatorward motion and moves down at low latitudes followed by a poleward motion [23,24]. Thus the density of atomic oxygen at high latitudes is depressed while it is enhanced at low latitudes. This could be the reason for lower strengths of response observed by the high latitude station during major positive storms.

If the storm time energy inputs to the high latitude are strong, Joule heating will be rapid. Also, the local thermospheric temperature rise during magnetic storms will cause higher recombination rates for atomic oxygen which in turn causes lower ionisation density and thus total electron contents [25,26]. Thus negative storm effects are more predominant and the high latitude station observes higher strengths of response during weak negative storms (Figure 3).

In addition the composition changes, movement of mid latitude trough is another reason for producing severe negative ionospheric responses *i.e.* a mechanism operative at mid latitudes for producing negative phase is the equatorward movement of the mid latitude trough, a region of lower electron densities which is the ionospheric manifestation of the plasmapause. Under quiet geomagnetic conditons, the Earth's plasma sphere extends to L ~4–5. During geomagnetic storms the plasmasphere is compressed, causing the trough to move to lower latitudes. This could result in a significant drop in TEC at mid latitudes [27]. This could be the reason for the higher strengths of response observed by mid latitude station during major negative storms.

The short duration positive storm effects are caused by the travelling atmospheric disturbances and the long duration positive storm effects by changes in the large scale wind circulation. As the intensity of storms (Ap) increases, the above causative mechanisms will be more active which, in turn, increases the TEC values during positive storms. This could be the reason for positive correlations generally observed between the strength and intensity during positive storms.

It is understood that, ionospheric storms are resulting from geomagnetic storms. If the intensity of geomagnetic storm is higher, the associated energy inputs like enhanced electric fields, currents and energetic particle precipitation will be more effective and they will cause quick ionospheric responses. Thus, the ionospheric responses will be maximised quickly and the time delay for producing the maximum ionospheric response will be smaller as the intensity io ionospheric response increases. This is the reason for the negative correlation between the time delay and intensity of ionospheric response.

It is noteworth that the present study has revealed a general negative correlation between the strength and intensity of negative weak storms for all the three latitudes, contrary to the previous studies where a positive correlation was observed for low latitude staions.

Ionospheric storms are global phenomena that can be studied using a variety of measurement and modelling techniques. Global first-principles theoretical models have now reproduced the global-scale characteristics of ionospheric storms, but local features during specific terms are difficult to accurately predict, largely due to uncertainties in the input required by the models.

The altered thermospheric circulation causes downwelling of the neutral atmospheric oxygen, which produces increase in NmF_2 and TEC. This is clearly seen in outputs of global first principles models such as NCAR, TGCM, TIGCM and CTIM. The International Reference Ionosphere (IRI) is a climatological model for magnetically quiet conditions [28]. Recently, the IRI working group has undertaken to develop methods for updating the IRI under ionospheric storm conditions.

5. Conclusion

A study on the latitudinal variations of the strength of the ionospheric response to positive and negative weak as well as major magnetic storms by considering low (Ramey), mid (Sagamore Hill) and high (Goose Bay) latitude stations during the years 1980-81 was conducted.

In the case of weak and major positive storms, the lowest strengths of response are shown respectively by the mid and high latitude stations, while the highest strength of response for both categories of storms, is shown by the low latitude station.

For weak and major negative storms, the lowest strengths of response are again shown respectively by the mid and high latitude stations; in contrast, the highest strengths are exhibited respectively by the high and mid latitude stations.

The strength of the response during major positive storms, in general, increases with decreasing latitude. A positive correlation was found to exist between the strength of the response and the intensity of storms during weak and major positive storms for the low latitude station, Ramey. A similar trend was also seen for low and mid latitude stations during major negative storms. However, in the case of weak negative storms, a negative correlation was found to exist between the strength of the response and the intensity of storms for all the three latitudes, contrary to the previous studies for low latitudes during negative storms. Also, a negative correlation is observed between the intensity and time delay for maximum ionospheric response, in the case of positive weak storms for low latitude and negative weak storms for high latitude.

Acknowledgment

K Unnikrishnan wishes to dedicate this paper to the memory of his Father, late Sri K N Sukumaran Nair.

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